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**ADVANCED LASER DIAGNOSTICS OF
COMPRESSIBLE FLOWS**



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14. ABSTRACT <p>Advanced laser diagnostics have been developed to study the fundamentals of supersonic flows for scramjet applications. Filtered Rayleigh scattering and planar laser-induced fluorescence (PLIF) techniques were developed and applied for measuring temperature and species in reacting and nonreacting flows. Fundamental studies of a cavity flame-holder in reacting and nonreacting supersonic flows were conducted. Several cavity-configuration and fueling schemes were employed, and combustion performance was documented. Raman scattering was utilized to measure the time-averaged equivalence ratio of cavity fueling. OH-PLIF was used to mark the reaction zone of the combustion and aid the optimization of fueling. An isolator of rectangular cross section with adjustable divergence angles has been evaluated for different inlet Mach numbers. Shock structures and fluctuations of shock position were also identified at various Mach numbers, divergence angles, and pressure ratios. The potential application of a plasma torch as an alternative ignition source for the scramjet combustor was also investigated through experimental and CFD studies. Maintenance and upgrade of the test facility and support of testing were performed.</p>						
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PREFACE

This final report summarizes tasks performed during the period 17 March 1997 through 17 January 2003 under Air Force Contract F33615-97-C-2702. The contract was administered by the Propulsion Directorate of the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base (WPAFB), OH, with Dr. Thomas A. Jackson and Dr. Jeffrey M. Donbar as Government Project Monitors. The report was prepared by Dr. Kuang-Yu Hsu and Dr. Tarun Mathur of Innovative Scientific Solutions, Inc. (ISSI). The authors acknowledge the editorial assistance of Ms. Marian Whitaker.

1. INTRODUCTION

The objective of this program was development of advanced diagnostics to aid the understanding of the fundamentals of supersonic flows. The Rayleigh scattering technique was developed and applied for making measurements in high-speed environments. Fundamental studies of cavity-based flame holders and an isolator were conducted in Test Cell 19 of the Air Force Research Laboratory (AFRL/PRA). The potential of a plasma torch as an alternative ignition source for the scramjet combustor was also investigated through experimental and computational fluid dynamics (CFD) studies. Continuous maintenance and upgrade of the facility were performed in addition to support of combustion tests conducted in Test Cell 22 of AFRL/PRA. Tasks conducted over the contractual period are summarized in Section 2. Details of the documentation of Test Cell 22 data acquisition and control can be found in Appendix A. Appendix B contains a complete list of publications and presentations authored or coauthored by ISSI personnel during the period of performance of this contract.

2. WORK ACCOMPLISHED

2.1 Development and Applications of Advanced Laser Diagnostics

2.1.1 Filtered Rayleigh Scattering

Molecular filtered Rayleigh scattering (FRS) is based on the detection of elastic scattering of gas in the Rayleigh regime. Unlike scattering from particles, scattering from molecules is affected by the thermal motions of the fluid. The spectral profile of the molecular/scattered light differs from that of incident light. The scattered intensity is proportional to the density, and the Rayleigh scattering-frequency line width is a function of the temperature due to thermal molecular motions.

Dr. Campbell Carter (AFRL/PRA) and Mr. Jim Crafton (ISSI) collaborated with Dr. Greg Elliott (Rutgers University) in developing the FRS technique. An iodine cell containing a controlled amount of iodine vapor was designed, fabricated, and tested. The frequency of the narrow-line laser is tuned to the absorption band of molecular iodine. The signal from particle scattering is absorbed by the filter, while Doppler-shifted and broadened scattering from the gas is transmitted. This technique has been applied in making planar measurements of density, temperature, and bulk flow velocity.^{1, 2, 3, 4}

2.1.2 Other Applications of Laser Diagnostics

Other advanced laser diagnostics have been developed for measuring species (such as CH, OH, and NO) and flow quantities in reacting and nonreacting flows; in-house research as well as collaborative efforts with universities have been carried out.^{5, 6, 7, 8, 9, 10}

2.2 Plasma Torch Study

A plasma-assisted ignition study was conducted by Dr. Lance Jacobsen, a National Research Council (NRC) postdoctoral researcher, in collaboration with Dr. Campbell Carter and Mr. Jim Crafton. In the ambient environment, the plasma torch was tested with a nitrogen feedstock at power levels ranging from 0.5 to 4 kW. Two anode geometries were tested: a constricted, sonic orifice and a divergent 45-degree nozzle. A small calorimeter was constructed to quantify the thermal efficiency of the plasma torch for various current levels and flow rates. NO planar laser-induced fluorescence (PLIF) and Schlieren images were taken for the plasma-torch plume to examine the formation of NO in the jet shear layer as well as the interactions between the structures in the jet and in the arc column. The plasma-torch jet temperature above the arc region was measured simultaneously with the NO-PLIF technique using FRS. The results revealed that the sonic orifice had a higher thermal efficiency than the divergent nozzle. The NO intensity was observed to increase with increased power and decreased flow rate, as expected based on the

thermal-NO production mechanism. Further, the highest NO-intensity regions were measured directly above the arc and in the entrainment region corresponding to the arc-attachment zone on the anode because of the corresponding high temperatures in these regions. Instantaneous kernels of high NO intensity were observed in the vicinity of the hot pockets of nitrogen plasma produced from the unsteady arc-heating process. The details of this study were documented by Jacobsen, et al.¹¹

Evaluation of the interactions of a direct current (DC) plasma torch and another pulsed alternating current (AC) plasma igniter with an ethylene fuel jet in a low-temperature supersonic crossflow was conducted by Drs. Lance Jacobsen and Campbell Carter, in conjunction with Dr. Kuang-Yu Hsu and Mr. Jim Crafton of ISSI.¹²

2.3 Fundamental Study of Cavity Flame Holder

A cavity has been proposed as a flame-holding device in the flowpath of a scramjet. Fundamental studies of cavities in supersonic flows have been conducted in Test Cell 19 of ARFL/PRA. The length, depth, and angle of the aft-wall of the cavity were varied and the results compared with those obtained from CFD analysis. The drag loss was found to increase with cavity length and angle of the aft-wall.¹³ However, the increase in drag also indicates increased air entrainment into the cavity, which is essential for cavity combustion.

To understand the fuel distribution in the cavity region, Raman scattering was employed for measuring the time-averaged equivalence ratio in the vicinity of the cavity. Ethylene was injected through a 15-degree injector upstream of a cavity. The nonreacting experiment was conducted at $M = 2$ mainstream flow with various fuel-injection pressures. The shock train was positioned near the cavity region to simulate the heat release resulting from combustion. The Raman-scattering and shadowgraph images illustrated the strong influence of the shock system on fuel distribution. The shock/boundary-layer interactions at the leading edge of the cavity cause the fuel to be diverted away from the cavity. This observation helps to explain the cavity-flame blowout in some combustion tests conducted at AFRL/PRA.¹⁴

A series of cavity combustion tests was conducted to evaluate the combustion stability of a cavity with fixed geometry. Tests were conducted at $M = 2$ and $T_0 = 500$ °F, with ethylene fuel injected at various streamwise locations around the cavity. Backpressure was also imposed to position the shock system near the cavity for simulating conditions of potential flame blowout. Three fuel-injection locations were tested: 1) normal injection upstream of the cavity, 2) normal injection inside the cavity, and 3) tangential injection at the forward-facing ramp. The results showed that the cavity flame was sustained with all three fuel-injection schemes, and the cavity ramp injection demonstrates the highest fuel turndown ratio. When the shock train was positioned near the cavity, the only sustained cavity combustion was observed with the ramp-injection scheme. In conclusion, direct fueling of the cavity provides a range of stable combustion. Increased residence time and mixing through cavity ramp-injection offers a wider range of stable cavity combustion, and the applied shock system has minimal effect on

combustion. Another series of combustion tests was conducted to study the potential of cavities in tandem as a means of further improving flame-holding, mixing, and ignition for main fueling in the scramjet combustor. This study will be summarized in detail and presented at the ISABE Meeting in Cleveland, Ohio, in 2003.

2.4 Isolator Study

A fundamental study of isolator performance was conducted in a rectangular duct at $M = 2$ and $M = 3$ flows. The flowpath consists of a constant cross-sectional section (2 inches high by 6 inches wide by 8 inches long) connected to the exit of the facility nozzle, followed by a divergent bottom wall. The bottom wall was configured at a different divergence angle of 0, 1, or 2 degrees. The shock train was created by a backpressure valve located at the exhaust section. The position of the shock was controlled by the position of the backpressure valve. A normal shock train was observed at $M = 2$ flow, with a steep pressure gradient across the shock system. An oblique shock train was observed under $M = 3$ conditions, with an oscillating pressure rise across the shock system due to a series of compression and expansion processes. The shock system was typically unsteady, even under fixed flow conditions and was most unsteady at a 0-degree divergence angle. A CFD study was also conducted with the same flowpath and flow conditions, and the trends agree well with the experimental observations. The isolator study provided basic validation of the CFD predictions and future direction and tools for isolator designs.

2.5 Test Facility and Scramjet Combustion Tests

2.5.1 Compressed Natural Gas (CNG) Vitiator

A CNG vitiator purchased from Johns Hopkins University (JHU) was installed in Test Cell 22. Initial results showed poor starting, a nonuniform exit-temperature profile, and incomplete combustion. Several modifications to the swirler and fuel-injection scheme were made in an attempt to improve vitiator performance with natural gas; however, on the whole, these attempts were unsuccessful.

The vitiator was redesigned with a dump flange for fuel injection and flame-holding. Shakedown tests with the $M = 2.7$ facility nozzle and natural gas vitiator were conducted at stagnation conditions as high as 2300 °R and 300 psia. The startup process, temperature profile, and combustion efficiency of the new vitiator were greatly improved. Additional effort is required to further improve the operation and efficiency of the vitiator.

2.5.2 Ground Demonstration Engine (GDE) Hardware and Testing

Various components of the GDE hardware were designed, fabricated, assembled, instrumented, and installed on the thrust stand. These components included the transition section, facility

nozzle(s), isolator, and combustor. Fuel-supply connections and water cooling of the GDE combustor were also completed.

Numerous combustion tests were conducted using gaseous ethylene and/or heated (1350 °R) liquid fuels (JP-7 or n-octane) at equivalence ratios between 0.8 and 1.0. Typical stagnation conditions ranged from 150 to 300 psia and 1800 to 2200 °R. Various fuel splits and combustor/cavity fueling schemes were tested. In most cases, combustion efficiencies were around 60 percent with the liquid fuels, and inlet unstart was observed near $\phi \sim 1$.

An air throttle or an ethylene pilot flame was used to initiate combustion. Both methods provided sustained mainstream combustion after deactivation/removal. Silane is being considered as another ignition source for the combustor as well as for the CNG initiator. Preliminary design, layout, and safety analysis of the silane system are complete, and installation is underway.

2.5.3 Heated-Fuel System

Pumps, power supply, cavitating venturi, and plumbing for the heated-fuel system were installed. Hardware and wiring were installed for remote control/monitoring of the heated-fuel system and power supply, and issues related to their safe, automated control were addressed; an appropriate failsafe was built into the control interface. Automated proportional-integral-derivative (PID) controls for the combustor fuel flow rate and fuel temperature were implemented. Signal conditioners were installed to isolate the fuel-heater-coil thermocouples from the data-acquisition system and to alleviate any common-mode voltage problems. The heated-fuel system has been operated successfully.

2.5.4 Data Acquisition (DAQ) and Control

DAQ, control processes, and performance calculation were transitioned to an Alpha workstation. Two analog input cards were added to the DAQ, increasing the number of analog input channels from 416 to 480. A shared-memory-transfer program was developed to replace the existing socket-based data transfer. Breakdown of functions in the legacy FORTRAN-based program FDAX and replacement with a suitable combination of Perl, C, and shell scripts has been initiated. Code was developed for real-time filename/time/record-number superposition on video recordings and has been integrated into the main DAQ code. New hard drives were installed on the Alpha workstation to provide expanded storage capability.

On-site support from the original author of the Kinetics Computer Automated Measurement and Control (CAMAC) Unix driver was arranged in an attempt to resolve some of the long-standing driver-related issues that caused intermittent input/output (I/O) errors. The 2962 peripheral component interconnect (PCI) host-controller boards and 3972 grand interconnect crate controller cards were also upgraded at Kinetic Systems. Plans were made for the development of a scanner by Integrated Process Automation and Control Technologies (IPACT) to optimize

communication between the CAMAC crates and the DAQ/control applications and avoid conflicts. Interfaces between this scanner and the user applications were developed in-house. The scanner has been extensively tested over the past several months, and its performance meets all expectations. Minor improvements to the scanner are still being made.

Graphical user interfaces (GUIs) were designed to monitor the water, wall, and fuel-manifold temperatures of the GDE combustor. Four-color alarms were implemented to enhance the user interpretation of the Vsystem displays. Multiple monitors were installed on the Windows personal computers (PCs) in Test Cell 22, and a Linux box for console displays is being set up to further improve monitoring efficiency for test-cell personnel. A totalizer was developed using Vscript, a scripting component of the Vsystem toolkit, to track octane consumption and ensure that the fuel heater would not run dry and incur damage.

The Pressure Systems Inc. (PSI) system firmware and DAQ software were upgraded. A hand-held personal digital assistant (PDA)-based checklist was developed to streamline and modernize the startup, operational, and shutdown procedures and checklists for the entire test cell. This approach has shown considerable promise, although some refinement is still needed. A program was developed for remote acquisition of fuel-farm-tank readings. Apart from easing the workload of test-cell personnel, this program will aid the Facilities Branch by providing automated status reports and inventory reconciliations. A Linux box was acquired and set up to support ongoing control upgrades in Test Cell 18. Details of the DAQ/control in Test Cell 22 can be found in Appendix A.

2.5.5 Instrumentation and Calibrations

Sonic venturis and various turbine flowmeters were calibrated at the Colorado Engineering Experiment Station. New orifice plates were installed in the 2-, 3-, and 6-inch air lines. Those for the 3- and 6-inch air lines were calibrated in-house against the sonic venturis at ambient and elevated temperatures.

The thrust-stand load cells were recalibrated. To evaluate any potential misalignment of the load-cell axis with the rig thrust axis, the measured load-cell force (LCF) (under vacuum conditions) was compared with theoretically predicted drag (product of projected exit area and pressure difference). These quantities compare to within 20 lbf (1 percent full scale of load cell), indicating that existing misalignment is not too severe.

To avoid problems with continual corrosion damage to turbine flowmeter bearings, a decision was made to use subsonic venturis for water flowrate measurements. Venturis for the vitiator, transition section, instrumentation section, nozzle, and isolator were sized and procured. These are currently being installed on the thrust stand.

A new dead-weight tester and alternative calibration devices were evaluated, and a Ruska dead-weight tester has been purchased for in-house calibrations of the PSI system pressure-calibration units (PCUs) and other pressure transducers.

2.5.6 Scramjet Combustion Studies

Combustion tests on the scramjet combustor were conducted in Test Cell 22 of AFRL/PRA. In-house research of flush-wall fuel injection and the cavity-based scramjet combustor has been documented in detail.^{15,16,17,18}

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APPENDIX A

Documentation of Test Cell 22 Data Acquisition and Control

A1. Overview

Robust and flexible DAQ and control systems are needed to meet the demanding and constantly evolving research requirements of complex test facilities such as Test Cells 18, 19, and 22. These systems must not only meet the present and near-term needs of scramjet-related testing but also provide the test cells with capabilities suitable for future advanced high-speed propulsion-research endeavors. Such endeavors potentially include (but are not limited to) mode-transition investigations in scramjets, combined-cycle studies, and transition between cycles in combined-cycle research.

With the increased focus on in-house scramjet research over the past few years, the need to upgrade the DAQ and control capabilities of the test cells has become a high priority. Since upgrades of this magnitude require considerable time and since research testing cannot be halted for extended durations, these upgrades must be accomplished through a cautious and phased approach to minimize adverse impact on ongoing research activities.

The following discussion is directed mainly toward the control issues in Test Cell 22-- the most complex of the three test cells operated by AFRL/PRA. Test Cell 19 is a relatively smaller cell, with simpler (nonvitrated and mainly noncombusting) control needs that are adequately met by the existing National Instruments/Visual Basic (NI/VB)-based system. Test Cell 18 is currently undergoing instrumentation/DAQ/control upgrades. Considerable crossover and overlap occur among the DAQ/control development activities of the three test cells, and strategies that are employed successfully in one test cell are usually transferred to the others. These common areas will be identified, where appropriate, in the following discussion.

A brief discussion of the evolution of the DAQ/control systems in Test Cell 22 will be presented in the next section to provide a meaningful context and historical perspective to the discussion of ongoing and proposed future activities to be described in subsequent sections. In these sections the problem identification and innovative problem solving approaches to past, present, and future issues are evident.

A2. Background

Until recently, the DAQ/control system in Test Cell 22 consisted of two CAMAC crates, one with cards for analog inputs (DAQ) and the other with cards for analog outputs (control). Each crate was connected to a separate Sun workstation via a fiber-optic small-computer system interface (SCSI), as shown in Figure A-1. A legacy FORTRAN-based program called FDAX was used to acquire and process data on the DAQ Sun. Relevant data and performance parameters were transmitted to the control Sun via sockets for control-related operations. The control user interface was based on a software package called LabTech. Several limitations were encountered with this configuration, making it unsuitable for the needs of high-speed propulsion research that had become the focus of efforts in Test Cell 22. These problems included the aging/non-Y2K (year two thousand)-compliant workstations as well as the control software's inflexible design/user control interfaces and nonscalable architecture, as described below.

The workstations were getting very old; with the (then) upcoming Y2K problem, no available operating-system patch was compatible with the existing CAMAC drivers. While the short-term solution was to roll the system date back 28 years, the practical solution was to replace the old workstations with a more powerful, faster, and contemporary system. Furthermore, the control software design and user interfaces were not user friendly, had no mouse-based control capability, and could display only a limited number of objects on the screen. These limitations rendered the workstation and control software configuration incompatible with the flexibility required in the control interface to respond to evolving research needs. Moreover, LabTech discontinued all support and development for Unix. The control system in this implementation also had no digital I/O capability; all on/off control and indication was performed manually via toggle switches and status lights.

A3. Alpha Workstation, Vsystem, and FDAX

As discussed previously, a cautious and phased approach in addressing these problems was required to minimize operational risk and adverse impact on ongoing research activities. In the first phase of upgrades, the control Sun (and LabTech software) was replaced with a newer and more powerful Alpha workstation that runs Vista Control System Vsystem software. The Alpha box is connected to the control crate via a high-speed grand interconnect. Figure A-2 is a schematic of this transition setup. The Vsystem toolkit allowed rapid development of databases, GUIs, and PID control scripts to perform the basic control functions. Since the Vsystem package is extremely user friendly, scalable, and flexible, it is capable of meeting the evolving demands of high-speed research activities. This package is supported on multiple platforms, has excellent and responsive technical support, and has an extensive user base—primarily, nuclear-reactor and particle-accelerator facilities in the U.S. and Europe.

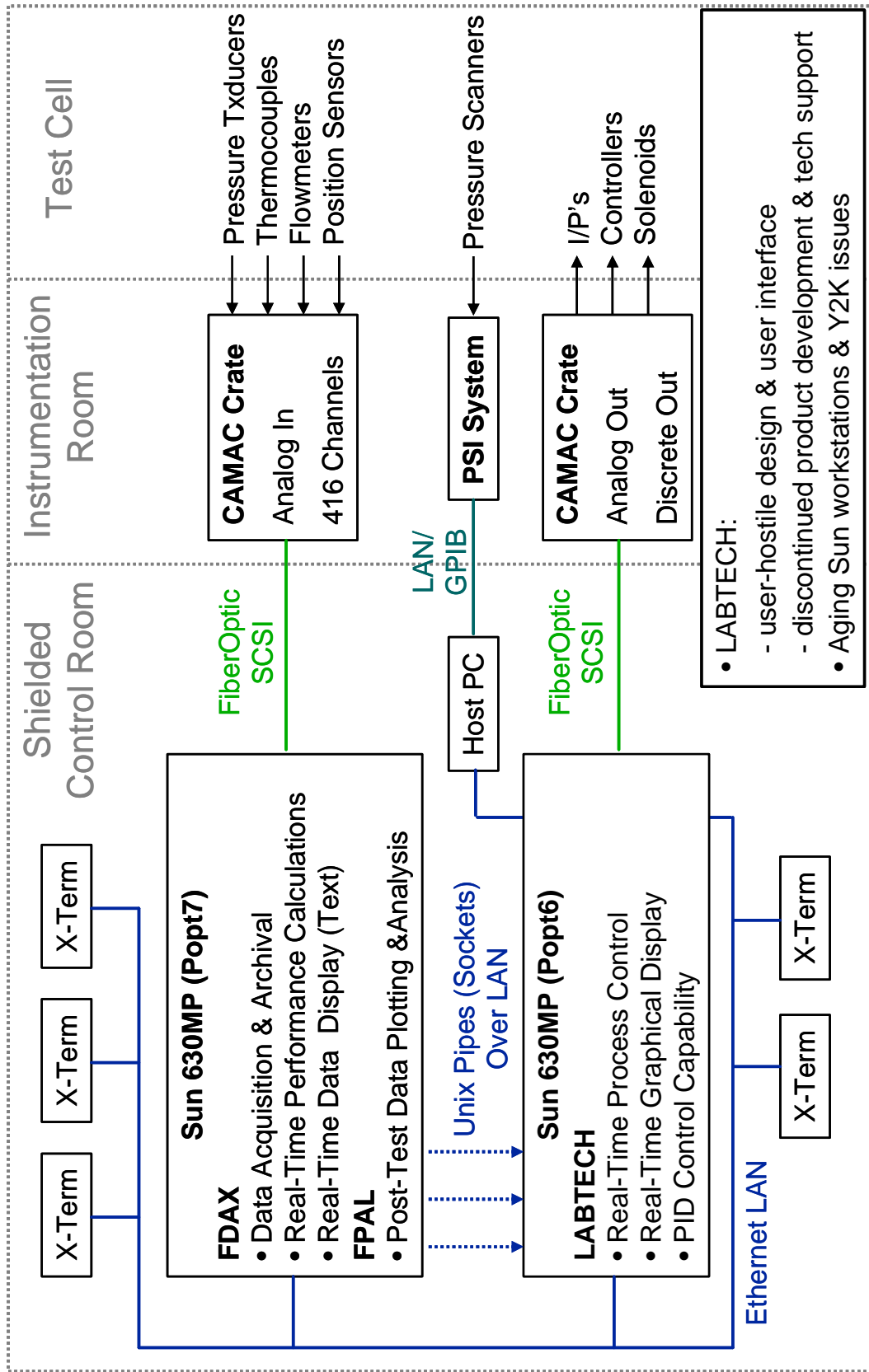


Figure A-1. Original Configuration: Sun Workstations with LabTech

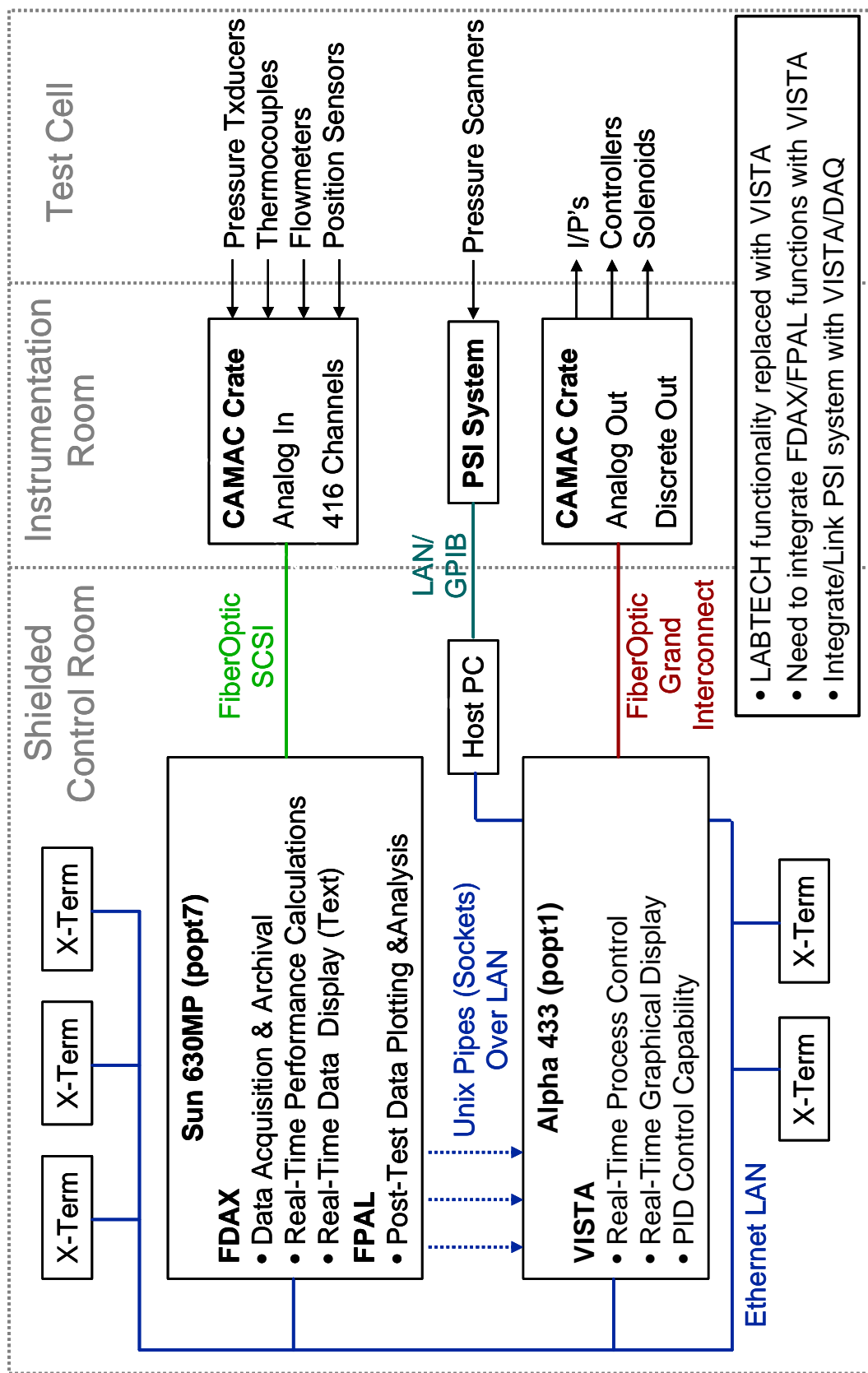


Figure A-2. Transition: Sun and Alpha Workstations with Vsystem

The DAQ side was unaffected by the above implementation and still served the control application with data over sockets. The next phase of upgrades involved porting the FDAX DAQ code to the Alpha and decommissioning the DAQ Sun. Concurrently with this porting process, the number of analog input channels was increased to 480 to accommodate the growing instrumentation load. Both CAMAC crates were now linked via a high-speed grand interconnect to the Alpha workstation. A schematic of the current DAQ/control setup in Test Cell 22 is shown in Figure A-3.

Presently, custom-designed Vsystem GUIs control most of the processes and support systems in Test Cell 22, including the research airflow, CNG vitiator, combustor fuel flow, heated-fuel system, and fuel-heater power supply. The health of the test hardware, including the combustor, vitiator, facility nozzle, isolators, and thrust stand is also monitored via GUIs. Automatic PID control loops with user-adjustable tuning constants are used to establish stable test conditions. Automated safety-monitoring programs are being developed that will take appropriate failsafe actions if one or more process parameters go out of safe bounds. The various text-based data displays served by FDAX will be phased out and replaced with more intuitive Vsystem GUIs. A Vsystem-based GUI and control interface is being designed for the upcoming silane ignition system in Test Cell 22. The silane system will replace the air throttle and serve as an ignition aid for both the combustor and the vitiator.

A4. Scanner

When all user applications (FDAX and various PID control scripts) were running asynchronously and independently, the potential for I/O conflicts increased with the number of channels being read or controlled, the reason being that each channel accessed the CAMAC hardware directly, without regard to the activity of the other channels. Furthermore, since the overhead associated with the I/O of each individual channel is rather substantial, the communication over the grand-interconnect bus was sub-optimal. To resolve these issues, a scanner is being developed and tested to provide an intermediate layer between the user applications and the hardware. The scanner is smart in that it dynamically compiles a list of all of the I/O channels that must be accessed by user applications and employs this list to perform bulk I/O with the hardware, thus optimizing the communication throughput. The scanned hardware inputs are served to the appropriate user applications. Output operations required by the user applications are registered with the scanner and transmitted to the hardware via an output thread generated by the scanner process. This decoupling by the scanner of hardware I/O from the asynchronous and independent user applications eliminates the potential for I/O conflicts. A schematic of the scanner implementation is shown in Figure A-4. The scanner is currently being evaluated and integrated into the overall DAQ/control framework.

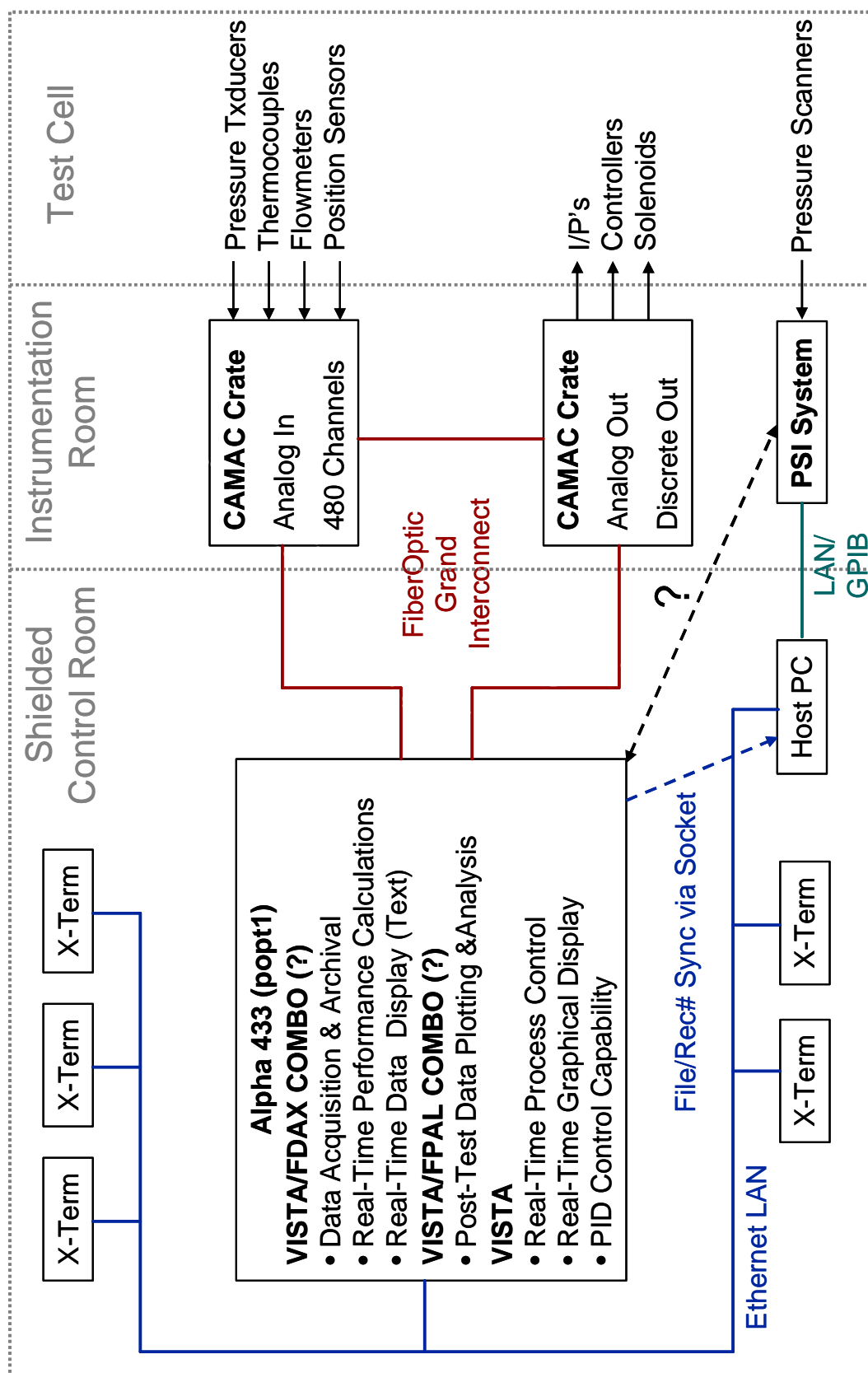


Figure A-3. Current Configuration: Alpha Workstation Running all Applications

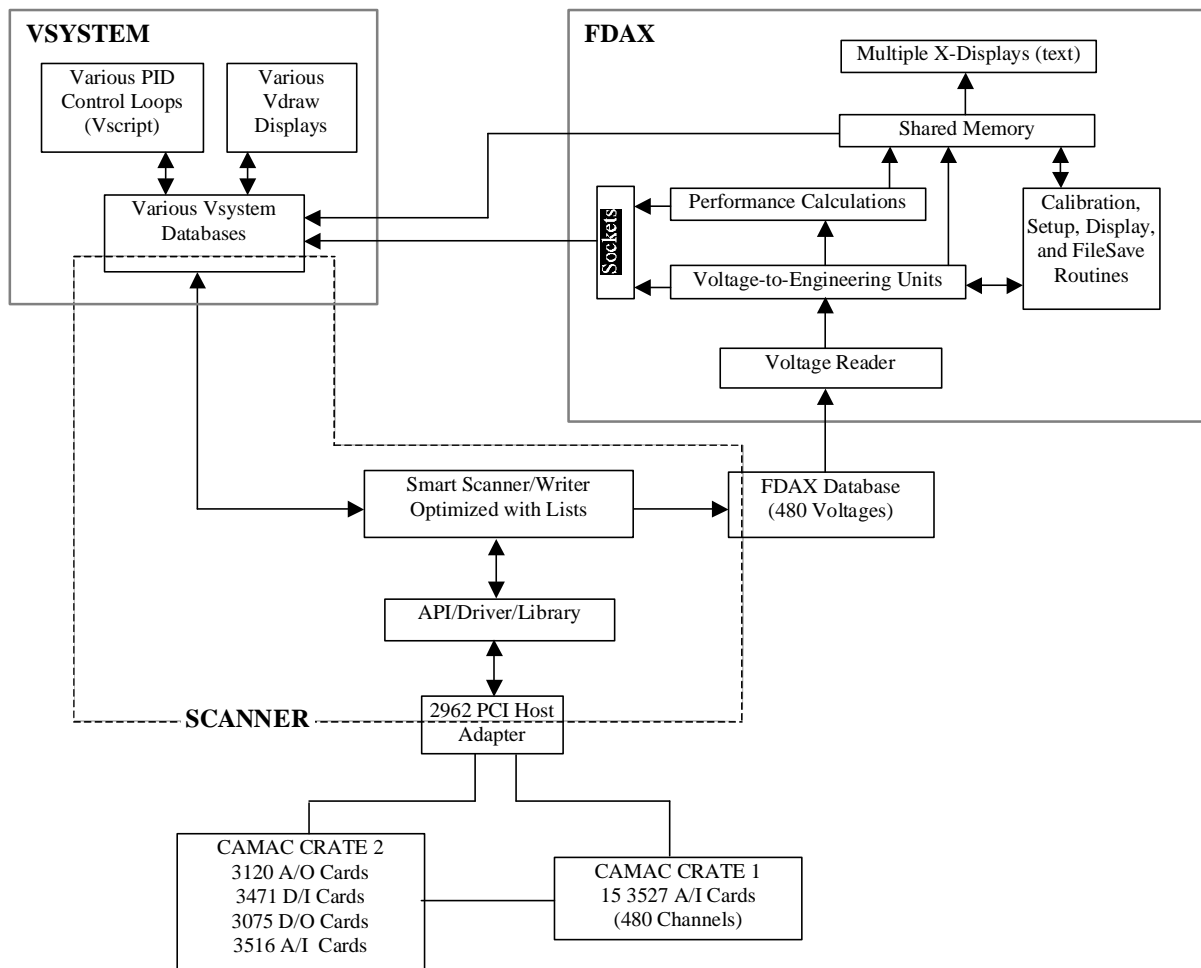


Figure A-4. Scanner Implementation

A5. Automatic PID Control

Since all of the inputs are now performed on a timed basis via the scanner, the existing PID Vscripts must be modified accordingly. In the prescanner mode, the PID scripts polled the hardware directly for input feedback and used the corresponding system time as a marker. The scripts will now require modification to permit use of the scanner-based timestamps instead and to ensure that the scanner base rate is sufficiently faster than the characteristic times of the controlled processes.

Furthermore, since most control valves in Test Cell 22 have equal-percentage trims to allow better control at the low end, the PID scripts should be upgraded to possess adaptive tuning capabilities. This will also aid accommodation of the changing process pressures and flow rates during (and between) combustion tests and eliminate the need for manual tuning at different valve positions and/or flow conditions.

A.6 Data Integration and Video Synchronization

Currently three primary information sets are associated with each scramjet test: data from FDAX, data from the PSI pressure scanners, and video recordings from the test-cell VCRs. These data sets are independent, and currently no direct method exists for accessing information from all three sets that corresponds to the same combustion event or instant in time.

As a first step in addressing this problem, all of the computer systems, including the PSI-system host PC, are synchronized to the same time server prior to testing. The PSI host PC, in turn, synchronizes the real-time clock in the PSI system. When the PSI data are acquired, the PSI system timestamp is saved along with the pressure data. This timestamp aids the manual correlation of data records between the PSI and FDAX data files.

To further improve this process, other approaches are being considered for FDAX/PSI data integration. One approach involves establishing communication [via transmission control protocol/internet protocol (TCP/IP) or alternative means] between the Alpha workstation and either the host PC or the PSI system directly. Another approach involves using the CAMAC 3585 pressure scanner interface card to read the PSI scanners and convey data directly into FDAX or Vsystem via the scanner. The current limitation of this approach is the inability of the 3585 card to perform other necessary PSI tasks such as purging and calibration. Kinetic Systems is currently considering the feasibility of either enhancing the functionality of this card or teeing this card into the existing PSI system setup where the nonscanning tasks could still be performed by the host PC and the scanned data could be intercepted by the 3585 card.

A microcharacter generator (MCG) is being used to synchronize video records with FDAX data. The FDAX filename, time, and record number are continuously passed from FDAX shared memory to the MCG via the Alpha serial port and superposed on the video signal entering the MCG video input. The combined signal is then sent to a VCR. This process is currently being evaluated prior to integration with the main DAQ programs. Future plans include supporting multiple VCRs with daisy-chained MCGs that receive the same text input from FDAX and superpose it on the different video signals received by each MCG.

A7. Phasing Out FDAX

The complexity, age, and nonstandard FORTRAN features of the legacy program FDAX make it extremely time consuming and difficult to port from one platform to another—a task that must be accomplished every few years with upgrades in computer hardware. This difficulty was especially evident in the recent port of FDAX from the Sun operating system (OS) to Tru64 running on the Alpha.

In the future the key functions provided by FDAX should be identified and replaced with more portable, standardized, and platform-insensitive equivalents in C or Vsystem. The first step in phasing out FDAX has already begun at the lowest level, with the scanner (programmed in C) replacing FDAX FORTRAN calls to the CAMAC hardware (see Figure A-4). The next layer of FDAX to be phased out will be the conversion (voltage-to-engineering units) routines. The built-in conversion-routine handlers in the Vsystem databases will replace the voltage-reader and voltage-to-engineering-units components of FDAX. The Vsystem FDAX database will continue to contain the raw scanner voltages in its internal representation and will also have the converted engineering values in its external representation. It is conceivable that, except for the performance-calculation portion of FDAX, Vsystem components and C handlers could replace all of the other FDAX functions. The performance code could either continue to exist as a FORTRAN-callable routine of Vsystem or, if necessary, be translated to C.

A8. Sockets and Shared Memory

Two interprocess communication methods were required in the old two-computer setup: shared memory for FDAX to feed various text-based displays on the DAQ computer and sockets to serve the same information to the control computer running LabTech or Vsystem. With all user processes being consolidated on the single Alpha workstation, the use of both methods is redundant and consumes unnecessary system resources. Furthermore, implementation of the sockets was very rigid and not amenable to changing research needs.

The socket-based link between FDAX and Vsystem databases will be phased out and replaced by shared-memory-based data transfer. A preliminary version of the shared-

memory client is already undergoing testing and has met all requirements to date. The shared memory implementation will be extremely dynamic, flexible, and capable of accommodating needed changes and expansion. Furthermore, since the Vsystem databases are essentially shared-memory entities, they will eventually replace the shared memory and clients. The final form of the system will then have two databases: 1) the Vsystem FDAX database with voltages and corresponding engineering values (in its internal and external representations, respectively), and 2) a performance-parameter database fed by the performance-calculation routine. The various Vsystem GUIs and scripts can then directly access the data from these two databases.

A9. Migration

Plans must be made for the long-term continuity of DAQ and control activities in support of high-speed propulsion research. Since the Alpha chip is being discontinued and no plans have been formulated to support Tru64 on the next-generation Itanium processor, a worthy successor to the Alpha workstation must be found. The stability of the OS and the ease of portability of the Vsystem and FDAX applications are two of the major considerations in making this choice. Based on the currently available options, Linux appears to be a promising candidate.

A Linux-based control system is being set up in Test Cell 18 as part of the ongoing instrumentation, data-acquisition, and control upgrade. Appropriate drivers and API libraries will also be developed. The Vsystem and scanner experience and knowledge base from Test Cell 22 can be readily ported to the Test Cell 18 Linux box, which expedites the development and learning curve. This will standardize the control applications, environments, and interfaces between the two test cells. The Linux system developed in Test Cell 18 will be a mature candidate for migration to Test Cell 22 when the Alpha workstation is phased out in a few years. In the event of a premature catastrophic failure of the Alpha box, the lead time in migrating the Linux system from Test Cell 18 to Test Cell 22 should be very short, causing only minimal adverse impact on ongoing research activities.

A10. Instrumentation Upgrades

Air-flow measurements in Test Cell 22 are usually accomplished using orifice plates in the 2-, 3-, and 6-inch air supply lines. The orifice plates were a logical choice, given the spatial constraints imposed by the expansion loops in the supply piping and the accuracy requirements (about 2 percent) of prescramjet testing in Test Cell 22,. However, the stricter uncertainty requirements of current scramjet testing and future projects slated for Test Cell 22 demand more accurate airflow measurements and much smaller fluctuations than those inherent in orifice plates.

Options are being considered for replacing the air-system orifice plates with venturi flowmeters. Venturis offer higher accuracy (1 percent or better with appropriate calibration) and significantly reduce the potential for fluctuating flow readings. Preliminary calculations indicate that a 3-inch and a 6-inch subsonic venturi will adequately cover the range of flow conditions required for current and future research needs, based on the anticipated envelope of air flow rates, supply pressures, and temperatures. The installation of the venturis will necessitate a substantial modification to the air supply plumbing layout in the test cell, and the optimum approach for accomplishing this change is being sought. Addition of isolation valves to the air supply lines and replacement of the aging bleed/vent valve are also being considered as a part of this upgrade.

Since all of the test hardware in Test Cell 22 is water cooled, the water flow through each component must be monitored for accurate energy balance. The turbine-based flowmeters for water-flow measurement are being replaced by venturis because the turbine bearings were constantly afflicted with corrosion from tower-water additives. Flow straighteners are being evaluated to minimize fluctuations in the venturi differential-pressure measurements.

A11. Calibrations

Because of limited research needs in the past, no formal system was established for regular calibration of test-cell instrumentation. The need for higher data accuracy in ongoing and future research requires reliable instrumentation with appropriate calibration traceability. A regular calibration schedule should be initiated for all test-cell instrumentation, including the sonic nozzles (used for in-house calibration of orifice plates) and various flowmeters that must be shipped off site. Instruments to be calibrated in-house include thrust-stand load cells, discrete pressure transducers, and orifice plate; calibration data will be documented and archived. Calibration data from the PSI transducers are automatically stored on PC and backed up with the pressure data. Recently a dead-weight tester was ordered for periodic calibrations of the secondary calibrators in the PSI system. A protocol for documentation of the dead-weight-tester calibrations will be instituted in the near future.

A112. Documentation

The dynamic nature of the research in the test cells requires frequent modifications to test hardware, support facilities and equipment, instrumentation, calibrations, software, and operating procedures. Documentation of these changes and upgrades is an important part of test-cell operations for historical purposes and to ensure safe operation.

Currently most modifications to the test-cell support systems and test hardware are documented in the form of engineering drawings and digital photographs. The drawings are archived in the facility database system as well as on each designer's PC; the photographs are

archived on the Propulsion Directorate (PR) server as well as via hardcopy. Recently, efforts have been initiated to make printouts of detailed instrumentation layouts with cross-referenced channel names, numbers, locations, etc., readily available on short notice for ease of troubleshooting and diagnosis during a test.

A detailed and comprehensive paper checklist, nearly 20 pages in length, is currently used for the startup, operation, and shutdown of the test cells and all of the complex support systems. The checklist is being ported to a hand-held PDA and can be modified on the PC and downloaded to the PDA prior to each test. In addition to the convenience of carrying a small PDA for the startup and shutdown portions of the checklist, the annotated checklist can be uploaded back to the PC for long-term storage, eliminating the need for a hardcopy. While this PDA approach holds considerable promise for the sequential startup and shutdown checklists, it is not appropriate for the operational checklist because of the repetitive nature of testing. Options are being considered; in the meantime, the operational checklist will be performed using a hardcopy (having significantly fewer pages than the entire checklist), while the startup/shutdown will employ the PDA.

Maintenance and documentation of all of the in-house software (especially the legacy code FDAX) are areas that need considerable improvement. Software conflicts are caused when multiple users are working on different elements of the same source code; the result is that multiple versions of source and executable code can be found everywhere in the system. Maintaining multiple versions of code in such an unorganized manner creates confusion and uncertainty in determining which version is the most stable for use in a live system. All source code will be placed under a source-code control system (SCCS). The SCCS will maintain documented revisions of all of the text source files. Each user must check out a version of the code before making modifications. Only the user who has the code checked out can make changes to it. The code will be checked in to the SCCS after the necessary modifications have been made. The SCCS will maintain all of the revisions in an organized manner, which will eliminate the need for multiple copies of the revised code. This will also provide a means of documenting the author and reasons for each revision and allow easy retrieval of past versions of code.

APPENDIX B

List of Publications and Presentations of ISSI Personnel

C. D. Carter, A. S. Nejad, and G. S. Elliott, "Feasibility of Plasma-Based Drag Reduction for a Scramjet Combustor," presented at the Weakly Ionized Gases Workshop, 9-13 June 1997, USAF Academy, CO.

G. S. Elliott, N. Glumac, C. D. Carter, and A. S. Nejad, "The Measurement of Two-Dimensional Temperature Field using Filtered Rayleigh Scattering," Presented at the 1997 ASME Fluids Engineering Division Summer Meeting FEDSM'97, 22-26 June 1997, Vancouver, B.C., Canada, and published as Paper No. FEDSM97-3094.

R. D. Gould, C. D. Carter, J. Donbar, and A. S. Nejad, "Three-Dimensional Mixing Study of Reacting and Isothermal Flow behind a Bluff Body Flameholder with Normal Fuel Jet Injection," presented at the 1997 ASME Fluids Engineering Division Summer Meeting FEDSM'97, 22-26 June 1997, Vancouver, B.C., Canada, and published as Paper No. FEDSM97-3097.

G. Elliott, A. Mosedale, M. Gruber, A. Nejad, and C. Carter, "The Study of a Transverse Jet in a Supersonic Cross-Flow Using Molecular Filter Based Diagnostics," presented at the 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 6-9 July 1997, Seattle, WA, and published as AIAA Paper No. 97-2999.

P.-K. Wu, M. Shahnam, K. Kirkendall, C. Carter, and A. Nejad, "Expansion and Mixing Processes of Underexpanded Supercritical Fuel Jets Injected into Superheated Conditions," presented at the 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 6-9 July 1997, Seattle, WA, and published as AIAA Paper No. 97-2852.

J. Donbar, C. Carter, and J. Driscoll, "Simultaneous CH Planar Laser-Induced Fluorescence and Particle Imaging Velocimetry in Turbulent Nonpremixed Flames," presented at the 1997 Gordon Research Conference on Physics and Chemistry of Laser Diagnostics in Combustion, 6-11 July 1997, Plymouth, NH.

K. Watson, K. Lyons, J. Donbar, and C. Carter, "Scalar and Velocity Field Measurements in a Lifted CH₄-Air Diffusion Flame," presented at the 1997 Gordon Research Conference on Physics and Chemistry of Laser Diagnostics in Combustion, 6-11 July 1997, Plymouth, NH.

J. M. Donbar, J. F. Driscoll, and C. D. Carter, "Simultaneous CH Planar Laser-Induced Fluorescence and Particle Imaging Velocimetry in Permanently Blue Nonpremixed Turbulent Jet Flames," presented at the Fall Technical Meeting of the Eastern States Section of the Combustion Institute, 27-29 October 1997, Hartford, CT.

C. D. Carter, J. M. Donbar, and J. F. Driscoll, "Simultaneous CH Planar Laser-Induced Fluorescence and Particle Imaging Velocimetry in Turbulent Non-Premixed Flames," *Applied Physics B* **66**, 129 (January 1998).

M. Gruber, K. Jackson, T. Jackson, T. Mathur, and K.-Y. Hsu, "Investigations of Shock Trains in Rectangular Ducts," presented at the 35th JANNAF Meeting, 1998.

J. M. Donbar, J. F. Driscoll, and C. D. Carter, "Simultaneous CH Planar Laser-Induced Fluorescence and Particle Imaging Velocimetry in Turbulent Flames," presented at the AIAA 36th Aerospace Sciences Meeting and Exhibit, 12-15 January 1998, Reno, NV, and published as AIAA Paper No. 98-0151.

C. D. Carter, W. L. Weaver, A. P. Mosedale, G. Elliott, and T. J. Beutner, "On the Use of Planar Doppler Velocimetry," presented at the AIAA 36th Aerospace Sciences Meeting and Exhibit, 12-15 January 1998, Reno, NV, and published as AIAA Paper No. 98-2809. Received AIAA Best Paper Award from AIAA Fluid Dynamics Technical Committee.

S. A. Arnette, G. S. Elliott, A. D. Mosedale, and C. D. Carter, "A Two-Color Approach to Planar Doppler Velocimetry," presented at the AIAA 36th Aerospace Sciences Meeting and Exhibit, 12-15 January 1998, Reno, NV, and published as AIAA Paper No. 98-0507.

J. M. Donbar, J. F. Driscoll, and C. D. Carter, "Simultaneous CH Planar Laser Induced Fluorescence and Particle Imaging Velocimetry in Turbulent Flames," presented at the Twenty-Third Annual Mini-Symposium on Aerospace Science and Technology, 3 April 1998, Dayton, OH. Received award for Best Presentation in Session 2A - Turbulence.

J. R. Gord, J. M. Donbar, G. J. Fiechtner, and C. D. Carter, "Vortex-Flame Interactions: Vortex Characterization by Two-Color PIV and Acetone PLIF," presented at the Twenty-Third Annual Mini-Symposium on Aerospace Science and Technology, 3 April 1998, Dayton, OH.

K. Jackson, M. Gruber, T. Mathur, W. Eakins, G. Streby, C. Smith, and F. Billig, "Design, Development, and Calibration of a Direct-Connect High-Enthalpy Supersonic Combustion Research Facility," presented at the Twenty-Third Annual Mini-Symposium on Aerospace Science and Technology, 3 April 1998, Dayton, OH.

K. Jackson, M. Gruber, T. Mathur, G. Streby, C. Smith, and F. Billig, "Calibration of a Newly Developed Direct-Connect High-Enthalpy Supersonic Combustion Research Facility," Presented at the Twenty-Third Annual Mini-Symposium on Aerospace Science and Technology, 3 April 1998, Dayton, OH.

K. Jackson, M. Gruber, T. Mathur, G. Streby, C. Smith, and F. Billig, "Calibration of a Newly Developed Direct-Connect High-Enthalpy Supersonic Combustion Research Facility," presented at the 8th International Space Plane Hypersonic Systems and Technology Conference, 27-30 April 1998, Norfolk, VA, and published as AIAA Paper No. 98-1510.

I. Vihinen, J. R. Gord, J. M. Donbar, G. J. Fiechtner, C. D. Carter, and J-C. Rolon, "Visualization of Vortex-Flame Interactions in a Counterflow Diffusion Flame," submitted in May 1998 to *Optical Diagnostics in Engineering*.

T. Beutner, G. Elliott, A. Mosedale, and C. Carter, "Doppler Global Velocimetry Applications in Large-Scale Facilities," presented at the 20th Advanced Measurement and Ground Testing Technology Conference, 15-18 June 1998, Albuquerque, NM, and published as AIAA Paper No. 98-2608.

G. J. Fiechtner, C. Carter, J. R. Gord, K. D. Grinstead, W. M. Roquemore, and J-C. Rolon, "Flame-Vortex Interactions in a Nonpremixed H_2/N_2 /Air Counterflow Burner," presented at the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 12-15 July 1998, Cleveland, OH, and published as AIAA Paper No. 98-3770.

J. R. Gord, J. M. Donbar, G. J. Fiechtner, C. D. Carter, and J-C. Rolon, "PIV and OH LIF Imaging of Flame-Vortex Interactions in an Opposed-Jet Burner," presented at the Ninth International Symposium on Applications of Laser Techniques to Fluid Mechanics, 16 July 1998, Lisbon, Portugal.

V. R. Katta, C. D. Carter, G. J. Fiechtner, W. M. Roquemore, J. R. Gord, and J-C. Rolon, "Interaction of a Vortex with a Flat Flame Formed Between Opposing Jets of Hydrogen and Air," Publication No. 4F01, presented at the Twenty-Seventh International Symposium on Combustion, 2-7 August 1998, Boulder, CO, and published in Proceedings of the Combustion Institute **27**, 587 (1998).

G. J. Fiechtner, C. D. Carter, J. R. Gord, J. M. Donbar, R. D. Hancock, and J-C. Rolon, "Experimental Study of the Annular Extinction of a Laminar Premixed H_2/N_2 -Air Flame in an Opposed Jet Burner," Poster W2DO2, presented at the Twenty-Seventh International Symposium on Combustion, 2-7 August 1998, Boulder, CO.

I. Vihinen, J. R. Gord, J. M. Donbar, G. J. Fiechtner, C. D. Carter, and J-C. Rolon, "Visualization of Vortex-Flame Interactions in a Counterflow Diffusion Flame," presented at the 8th International Symposium on Flow Visualization, 1 September 1998, Sorrento, Italy.

C. D. Carter, "Combined PLIF and PIV Imaging in Nonpremixed Flames," invited presentation at the 1998 OSA Annual Meeting and Exhibit, ILS 14th Interdisciplinary Laser Science Conference, 4-9 October 1998, Baltimore, MD.

G. J. Fiechtner, C. D. Carter, K. D. Grinstead, Jr., J. R. Gord, J. M. Donbar, and J. C. Rolon, "The Dynamic Interaction between a Flame and an Isolated Vortex," presented at the Fall Technical Meeting of the Combustion Institute, 26-27 October 1998, Seattle, WA.

M. Gruber, T. Jackson, K. Jackson, W. Donaldson, J. Donbar, T. Mathur, G. Streby, C. Smith, and F. Billig, "A Cavity-Based Fuel Injector/Flameholder for Scramjet Applications," presented at the JANNAF Meeting, 7-9 December 1998, Tucson, AZ.

M. Gruber, T. Jackson, R. Baurle, T. Mathur, and K. Hsu, "An Evaluation of the Near-Field Mixing Effectiveness of Proposed HyTech Combustors," presented at the JANNAF Meeting, 7-9 December 1998, Tucson, AZ.

K-Y. Hsu, C. D. Carter, V. R. Katta, and W. M. Roquemore, "Characteristics of Combustion Instability Associated with Trapped-Vortex Burner," presented at the AIAA 37th Aerospace Sciences Meeting and Exhibit, 11-14 January 1999, Reno, NV, and published as AIAA Paper No. 99-0488. Dr. Carter was Chairman of the session on Particle-Based Velocity-Field Imaging.

G. Elliott, N. Glumac, and C. D. Carter, "Molecular Filtered Rayleigh Scattering Applied to Combustion and Turbulence," presented at the AIAA 37th Aerospace Sciences Meeting and Exhibit, 11-14 January 1999, Reno, NV, and published as AIAA Paper No. 99-0643.

K. D. Grinstead, Jr., G. J. Fiechtner, C. D. Carter, J. R. Gord, P.-H. Renard, and J. C. Rolon, "Laser-Based Visualization of Vortex-Flame Interactions," presented at the Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy, 7-12 March 1999, Orlando, FL.

K. A. Watson, K. M. Lyons, J. M. Donbar, and C. Carter, "Scalar and Velocity Field Measurements in a Lifted CH₄-Air Diffusion Flame," *Combustion and Flame* **117**(1/2), 257 (April 1999).

G. J. Fiechtner, C. D. Carter, and R. S. Barlow, "Quantitative Measurements of CO Concentrations in Laminar and Turbulent Flames Using Two-Photon Laser-Induced Fluorescence," presented at the Twenty-Fourth Dayton-Cincinnati Aerospace Science Symposium, 9 April 1999, Dayton, OH.

H. Baust, T. J. Beutner, G. Elliott, C. D. Carter, and J. Crafton, "Development of Doppler Global Velocimetry for Application in the 7' x 10' SARL Wind Tunnel," presented at the Twenty-Fourth Dayton-Cincinnati Aerospace Science Symposium, 9 April 1999, Dayton, OH.

J. R. Gord, G. J. Fiechtner, K. D. Grinstead, Jr., C. D. Carter, P.-H. Renard, and J. C. Rolon, "Continuing Studies of Vortex-Flame Interactions," presented at the Dayton-Cincinnati Aerospace Science Symposium, 9 April 1999, Dayton, OH.

M. Gruber, K. Jackson, W. Donaldson, J. Donbar, T. Jackson, T. Mathur, G. Streby, C. Smith, and F. Billig, "Supersonic Combustion Experiments with a Cavity-Based Fuel Injector," Presented at the Twenty-Fourth Dayton-Cincinnati Aerospace Science Symposium, 9 April 1999, Dayton, OH.

M. Gruber, K. Jackson, J. Donbar, W. Donaldson, T. Jackson, C. Smith, and F. Billig, "Supersonic Combustion Experiments with a Cavity-Based Fuel Injector," T. Mathur, G. Streby, presented at the 35th Joint Propulsion Conference, 20-24 June 1999, Los Angeles, CA, and published as AIAA Paper No. 99-2102.

M. Gruber, R. Baurle, T. Mathur, and K. Hsu, "Fundamental Studies of Cavity-Based Flameholder Concepts for Supersonic Combustors," presented at the 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 20-24 June 1999, Los Angeles, CA, and published as AIAA Paper No. 99-2248.

G. J. Fiechtner, C. D. Carter, and R. S. Barlow, "Quantitative Measurements of CO Concentrations in Laminar and Turbulent Flames Using Two-Photon Laser-Induced Fluorescence," presented at the 33rd National Heat Transfer Conference, 15-17 August 1999, Albuquerque, NM, and published as Paper No. HTD99-298.

J. R. Gord, G. J. Fiechtner, C. D. Carter, P.-H. Renard, and J. C. Rolon, "Characterizing the Interaction of a Vortex with a Laminar Opposed-Jet Flame," presented at the 33rd National Heat Transfer Conference, 15-17 August 1999, Albuquerque, NM, and published as Paper No. HTD99-295.

P.-K. Wu, M. Shahnam, K. Kirkendall, C. D. Carter, and A. Nejad, "Expansion and Mixing Processes of Underexpanded Supercritical Fuel Jets Injected into Superheated Conditions," *Journal of Propulsion and Power* **15**(5), 642 (September-October 1999).

S. Gogineni, L. Goss, G. Fiechtner, C. Carter, F. Schauer, J. Gord, and J. Donbar, "Quantitative Visualization of Flowfields Using Two-Color PIV," presented at the 3rd International Workshop on Particle Image Velocimetry, 16-18 September 1999, Santa Barbara, CA.

J. M. Donbar, M. R. Gruber, T. A. Jackson, C. D. Carter, and T. Mathur, "OH PLIF Imaging in a Hydrocarbon Fueled Scramjet Combustor," presented at the JANNAF Meeting, October 1999.

K. A. Watson, K. M. Lyons, J. M. Donbar, and C. D. Carter, "Observations on the Leading Edge in Lifted Flame Stabilization," *Combustion and Flame* **119**, 199 (October 1999).

G. J. Fiechtner, J. R. Gord, C. D. Carter, K. D. Grinstead, Jr., V. R. Katta, P.-H. Renard, and J. C. Rolon, "Vortex Injection of Noble Gases in an Opposed-Jet Burner," presented at the Fall Technical Meeting of the Eastern Sates Section of the Combustion Institute, 11-13 October 1999, Raleigh, NC.

S. Williams, A. J. Midey, S. T. Arnold, P. M. Bench, A. A. Viggiano, R. A. Morris, L. Q. Maurice, and C. D. Carter, "Progress on the Investigation of the Effects of Ionization on Hydrocarbon/Air Combustion Chemistry," presented at the 9th International Space Planes and Hypersonic Systems and Technologies Conference, 1-4 November 1999, Norfolk, VA.

G. J. Fiechtner, P.-H. Renard, C. D. Carter, J. R. Gord, and J. C. Rolon, "Injection of Multiple Vortices in an Opposed-Jet Burner," *Journal of Visualization* **2**, 331 (2000).

K. A. Watson, K. M. Lyons, J. M. Donbar, and C. D. Carter, "Visualization of Multiple Scalar and Velocity Fields in a Lifted Jet Flame," *Journal of Visualization* **3**, 203 (2000).

J. M. Donbar, J. F. Driscoll, and C. D. Carter, "Reaction Zone Structure in Turbulent Nonpremixed Jet Flames—From CH-OH PLIF Images," J. M. Donbar, J. F. Driscoll, and C. D. Carter, *Combustion and Flame* **122**, 1 (2000).

K. A. Watson, K. M. Lyons, J. M. Donbar, and C. D. Carter, "Simultaneous Rayleigh Imaging and CH-PLIF Measurements in a Lifted Jet Diffusion Flame," *Combustion and Flame* **123**, 252 (2000).

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LIST OF ACRONYMS

<u>Acronym</u>	<u>Description</u>
AC	alternating current
AFRL	Air Force Research Laboratory
CAMAC	computer-automated measurement and control
CFD	computational fluid dynamics
CNG	compressed natural gas
DAQ	data acquisition
DC	direct current
FRS	filtered Rayleigh scattering
GDE	ground demonstration engine
GUI	graphical user interface
I/O	input/output
IPACT	Integrated Process Automation and Control Technologies
ISSI	Innovative Scientific Solutions, Inc.
JHU	Johns Hopkins University
LCF	load-cell force
MCG	micro-character generator
NI/VB	National Instruments/Visual Basic
NRC	National Research Council
OS	operating system
PC	personal computer
PCI	peripheral component interconnect
PCU	pressure-calibration unit
PDA	personal digital assistant
PID	proportional integral derivative
PLIF	planar laser-induced fluorescence
PR	Propulsion Directorate
PSI	Pressure Systems, Inc.
SCCS	source code control system
SCSI	small-computer system interface
TCP/IP	transmission control protocol/internet protocol
Vscript	scripting component of Vsystem toolkit
WPAFB	Wright-Patterson Air Force Base
Y2K	year two thousand